Technical Bulletin 108 September 1935

University of Minnesota
Agricultural Experiment Station

Moisture Movement in Coniferous Wood Below the Fiber-Saturation Point

Stanley J. Buckman and Louis W. Rees
Division of Forestry

UNIVERSITY FARM, ST. PAUL

University of Minnesota
Agricultural Experiment Station

Moisture Movement in Coniferous Wood Below the Fiber-Saturation Point

Stanley J. Buckman and Louis W. Rees
Division of Forestry

UNIVERSITY FARM, ST. PAUL

MOISTURE MOVEMENT IN CONIFEROUS WOOD BELOW THE FIBER-SATURATION POINT[1]

STANLEY J. BUCKMAN[2] and LOUIS W. REES[3]

In drying wood, containing moisture above the fiber-saturation point, the moisture may move to the surface as free water, as vapor, and as bound liquid. As Hawley (4) points out, no force arising from difference in concentration will cause free water to move through wood. Moisture gradients show, however, that the moisture content at the center of a piece of wood may be considerably reduced before the adjoining cell walls have reached the fiber-saturation point. These results indicate that a movement of free water does occur in the seasoning of some woods. Hawley says this movement is caused by capillary forces set up in the cell cavities and in the perforations of the pit membranes. He concludes that the amount of free water movement in drying wood, above the fiber-saturation point, depends on the number and size of the openings between the cells and on the relative amounts of air and water in the cell cavities.

Below the fiber-saturation point, water may move in wood as bound liquid and as vapor. Studies of moisture movement below the fiber-saturation point are thus somewhat simplified since the movement of free water need not be considered.

The diffusion of water through wood below the fiber-saturation point has been studied by Martley (6) and Stillwell (12), by maintaining different relative humidity conditions at opposite sides of a piece of wood and observing the moisture gradients and the rate of water movement through the wood after a constant rate of flow had been obtained.

Martley (6) limited his observations to moisture movement in the radial direction in Scotch pine. While his results did not show which of the two possible mechanisms of moisture movement was the more important, they did show that a more rapid movement of water through wood was obtained at the higher moisture contents.

[1] The authors wish to express their appreciation for helpful suggestions and criticisms given by Dr. Henry Schmitz, Chief of the Forestry Division, University Farm, St. Paul, Minn., and Dr. L. F. Hawley, Forest Products Laboratory, Madison, Wis.

[2] American Creosoting Company Fellow (1931 to 1934), University of Minnesota. Fellowship established by the American Creosoting Company of Louisville, Ky.

[3] Assistant Professor, Division of Forestry, University of Minnesota.

Stillwell (12) determined the moisture gradients for a number of different hardwoods when the moisture movement was in the different structural directions. His results did not agree with the moisture gradients that were expected for either vapor or bound-liquid movement. The rates of moisture movement in the longitudinal direction of oak, as he found them, were from about 1½ to 3 times those in the radial direction, and from about 2½ to 7 times those in the tangential direction. In ash, the rates of movement in the longitudinal direction varied, approximately, from 2½ to 7 times those in the radial and tangential directions.

Pidgeon and Maass (7) have studied the movement of moisture into wood below the fiber-saturation point. Samples of sapwood and heartwood of jack pine and white spruce were dried by a prolonged period of evacuation in the presence of phosphorus anhydride. After drying, the wood samples were permitted to take up moisture to equilibrium at a vapor pressure of 4.58 mm. of mercury and at a temperature of 23° C. It was found that for longitudinal movement the time to half-saturation for the heartwood of white spruce (sample thickness 1.4 cm.) was 2¼ times that for sapwood while for pine (sample thickness 0.95 cm.) the time for heartwood was about 7½ times that for sapwood. For radial movement in the heartwood of white spruce (sample thickness 0.65 cm.) the time to half-saturation was approximately 2½ times that for sapwood. A direct comparison of rates of movement in the radial and longitudinal directions was not possible because samples of the same thickness were not used. However, the results show that for sapwood and heartwood of white spruce the time to half-saturation for radial movement would have been at least 20 times that for longitudinal movement.

Pidgeon and Maass (7) believe that moisture moves in wood, below the fiber-saturation point, chiefly as vapor. In support of this view, they point to the much slower rates of moisture movement in the radial direction than in the longitudinal direction, and in the heartwood as compared with the sapwood. It should be noted, however, that the work of Pidgeon and Maass was done in the absence of air, and their results are comparable only to pressure permeability data. They cannot be considered, therefore, as representing the rates of diffusion of moisture in wood.

Only a small amount of information concerning moisture movement in wood is available. Since such information has been used as the basis for conclusions regarding the mechanism of moisture movement in wood, it has seemed desirable to study further the movement of moisture below the fiber-saturation point.

EXPERIMENTAL

Materials

Six different kinds of coniferous woods were used, namely, Norway pine (*Pinus resinosa* Solander), jack pine (*Pinus banksiana* Lambert), white spruce (*Picea glauca* [Moench] Voss), black spruce (*Picea mariana* [Miller] Britton, Sterns, and Poggenberg), tamarack (*Larix laricina* [DuRoi] Koch), and balsam fir (*Abies balsamea* [Linnaeus] Miller).

Blocks 2.5 by 2.5 by 5.0 cm. in size were prepared for the experiment. These dimensions in all cases were for the wood in the green condition.

Freshly felled logs of the different kinds of wood were used as the source of material, thereby insuring a knowledge of the history of the wood from the time of cutting to the time of use. Blocks of each wood were cut to conform to the three structural directions. Whenever possible, representative samples were obtained from both the heartwood and the sapwood of the same kind of wood.

Methods

Immediately after the blocks were prepared they were placed in a cabinet maintained at a relative humidity of 95 per cent and a temperature of 30° C.[4] After they had reached approximate equilibrium under these conditions, the humidity was reduced and the blocks allowed to lose moisture to approximate equilibrium with a lower humidity. This procedure was continued until the blocks were at equilibrium with the relative humidity condition of the laboratory. They then were transferred to a cabinet containing anhydrous calcium chloride and their moisture content reduced to approximately 5 per cent.

After drying, the blocks were coated with 12 coats of vulcanized rubber latex[5] followed by 3 coats of shellac. Previous tests had shown that this coating was practically impermeable to moisture. Only one of the square faces of the blocks was left uncoated, thus confining the movement of moisture to one structural direction of the wood. After the blocks were coated, they were returned to the cabinet containing

[4] A cabinet 150 cm. in length, 60 cm. wide, and 60 cm. deep was used in making the study. Air circulation in the cabinet was maintained by an electrically driven, eight-inch, Sirocco fan. Temperature was controlled by means of a dry bulb acting through a mercury switch relay which was connected to the heating coils. These coils were in a separate compartment below the test specimens. Humidity was controlled by a wet bulb also connected with a relay which in turn operated two type C Bahnson humidifiers. The moisture was added to the air before it was forced over the heating coils. From the heating coils, the air was forced over the test specimens in the upper part of the cabinet.

[5] Sold under the name of Vultex (formula F-129-1) by the Vultex Chemical Company of Cambridge, Mass.

anhydrous calcium chloride and left until repeated weighings showed a condition of equilibrium.

When the coated blocks were at equilibrium with the described conditions, five blocks were selected for each structural direction of each wood. These were placed in a cabinet maintained at a relative humidity of 95 per cent and a temperature of 30° C. At the end of three hours they were again weighed and the increase in weight calculated. The weighings were repeated thereafter at what seemed to be suitable intervals of time. The entire series of blocks was run at the same time, thereby eliminating the influence of minor fluctuations in humidity and temperature.

The oven-dry weight and oven-dry volume were determined for all of the blocks used in the study, after the coatings had been removed. The oven-dry weight was determined by drying at atmospheric pressure in an electric oven to a constant weight at 105° C. The oven-dry volume was obtained by the water displacement method. The moisture content is expressed in terms of the oven-dry weight.

Results

The data for the increase in moisture content with time, when the moisture movement was in the three structural directions of different kinds of coniferous wood, are given in Table 1 and are shown graphically in Figures 1, 2, and 3. The data for each structural direction are an average result for five blocks of wood.

Table 2 gives the data for each of the individual blocks of tamarack heartwood. These data can be considered typical of the variation obtained with different blocks of the same kind of wood when the moisture movement was in the same structural direction.

Figures 1, 2, and 3 show that there was a maximum variation, for the different kinds of wood, of about 3 per cent in the total moisture gain to equilibrium with 95 per cent relative humidity, when the moisture movement was in the longitudinal direction. It seems this variation can be attributed to differences in the maximum adsorptive powers of the different kinds of wood, or, at least, to a variation in this property for the particular samples obtained from the different kinds of wood. Stamm (10) has reported values for the fiber-saturation points of seven different coniferous woods, which show a comparable variation. The average moisture gain to equilibrium with 95 per cent relative humidity was about 20 per cent. This would correspond to an actual equilibrium moisture content of about 25 per cent, since the blocks had a moisture content of approximately 5 per cent when they were transferred to a relative humidity of 95 per cent.

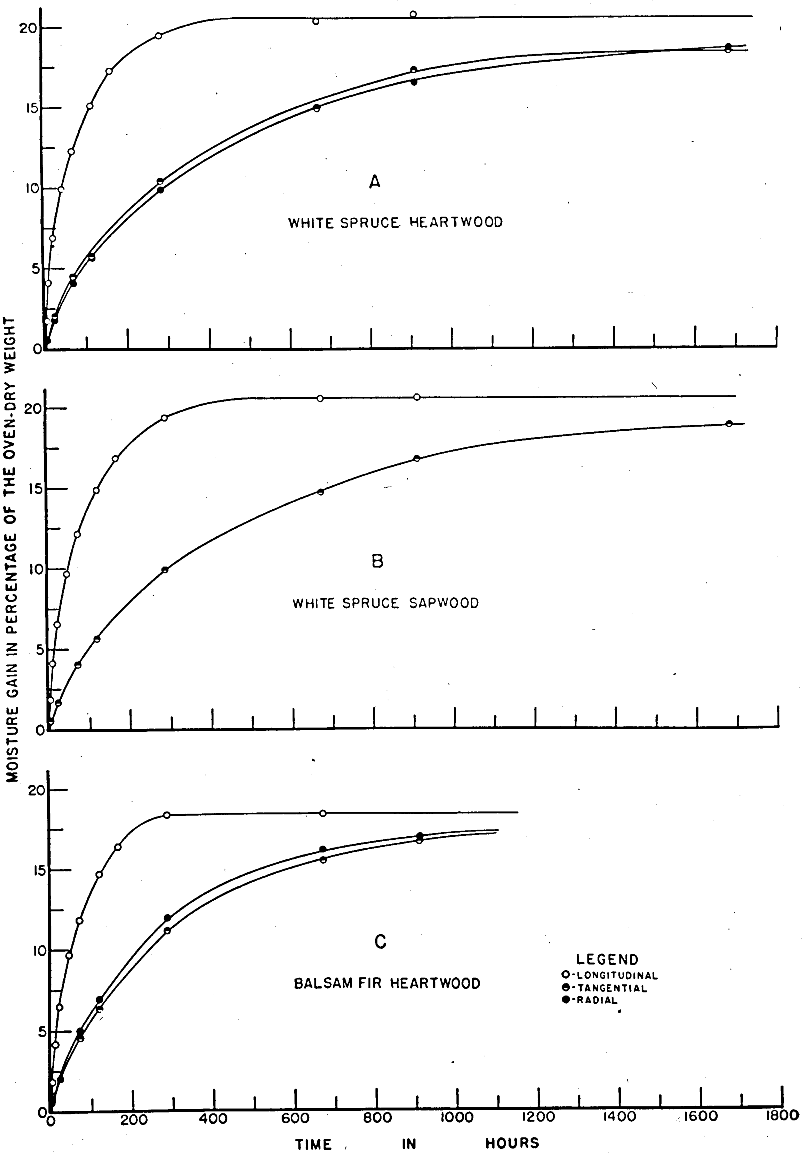

Fig. 1. Percentage increase in moisture content with time, when moisture movement was in the different structural directions of white spruce heartwood, white spruce sapwood, and balsam fir heartwood

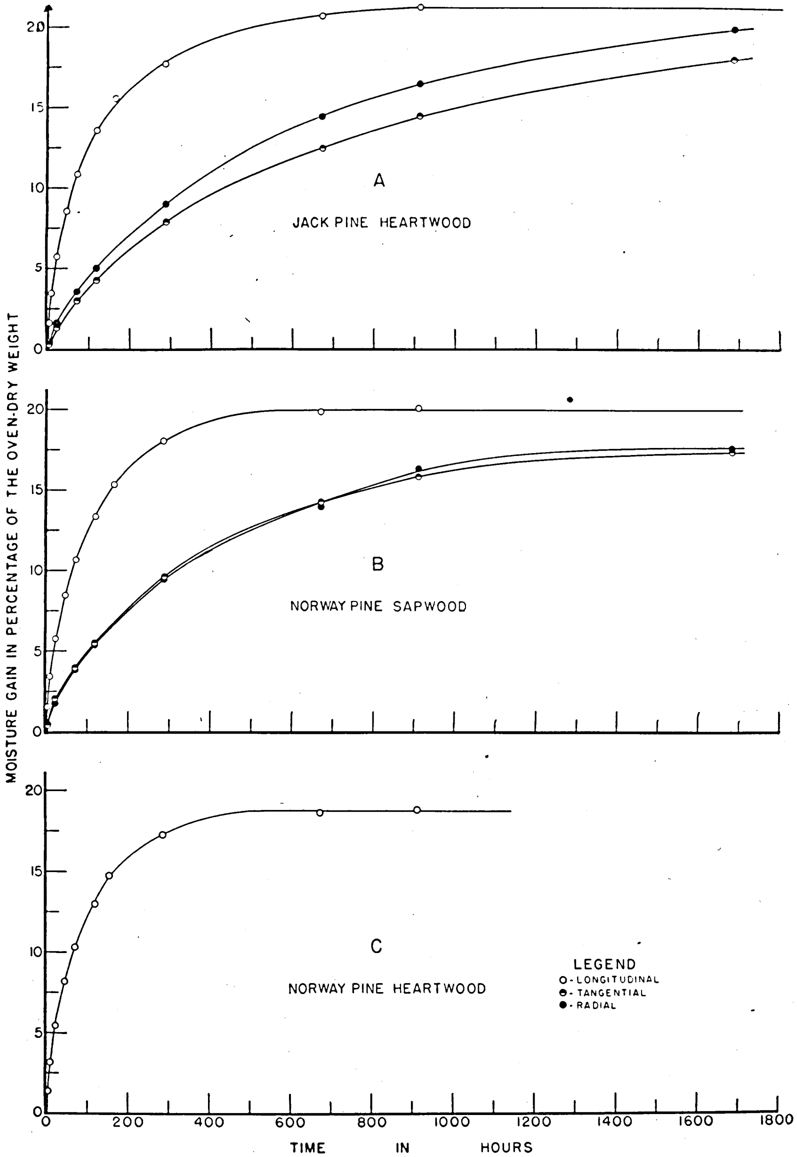

Fig. 2. Percentage increase in moisture content with time, when moisture movement was in the different structural directions of jack pine heartwood, Norway pine sapwood, and Norway pine heartwood

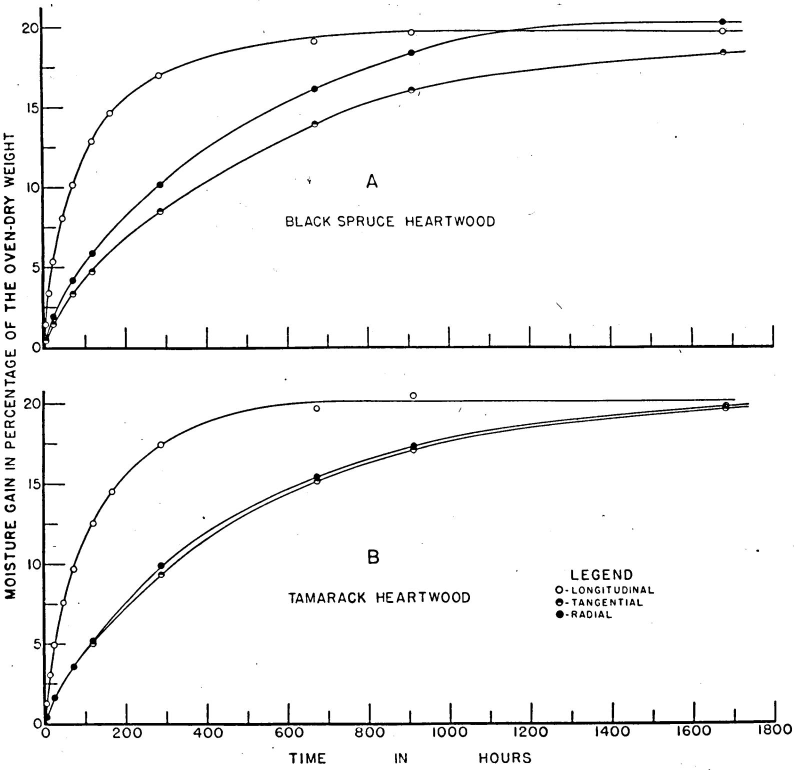

Fig. 3. Percentage increase in moisture content with time, when moisture movement was in the different structural directions of black spruce heartwood and tamarack heartwood

Table 1. Rate of Percentage Increase in Moisture Content of Several Coniferous Woods When the Moisture Movement Was Confined to the Different Structural Directions

Time, hours	Moisture gain in percentage of the oven-dry weight																				
	White spruce heartwood			White spruce sapwood		Balsam fir heartwood			Jack pine heartwood			Norway pine sapwood			Norway pine heartwood	Black spruce heartwood			Tamarack heartwood		
	Longi-tudinal	Radial	Tan-gential	Longi-tudinal	Tan-gential	Longi-tudinal	Radial	Tan-gential	Longi-tudinal	Radial	Tan-gential	Longi-tudinal	Radial	Tan-gential	Longi-tudinal	Longi-tudinal	Radial	Tan-gential	Longi-tudinal	Radial	Tan-gential
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1.75	0.51	0.53	1.83	0.50	1.82	0.55	0.53	1.60	0.44	0.28	1.54	0.47	0.42	1.32	1.38	0.48	0.38	1.26	0.42	0.41
10	4.10	...	...	4.10	...	4.14	...	...	3.43	...	...	3.42	...	...	3.12	3.34	...	...	3.04	...	...
23	6.85	1.80	2.02	6.59	1.67	6.58	2.09	2.07	5.73	1.61	1.30	5.75	1.75	1.84	5.42	5.32	1.89	1.46	4.91	1.59	1.57
46	9.94	...	...	9.67	...	9.63	...	...	8.54	...	...	8.46	...	...	8.16	8.04	...	...	7.57	...	...
71	12.28	4.04	4.21	12.12	3.99	11.80	5.00	4.53	10.81	3.49	2.92	10.64	3.81	3.92	10.28	10.16	4.14	3.29	9.67	3.54	3.14
119	15.10	5.67	5.70	14.87	5.63	14.72	6.91	6.40	13.50	4.97	4.22	13.29	5.37	5.48	12.95	12.86	5.85	4.70	12.52	5.19	5.03
166	17.28	...	...	16.81	...	16.46	...	...	15.50	...	...	15.34	...	...	14.73	14.64	...	...	14.50	...	...
287	19.46	9.87	10.38	19.35	9.89	18.34	11.97	11.16	17.63	8.94	7.80	18.03	9.45	9.59	17.28	17.09	10.14	8.48	17.47	9.89	9.32
671	20.27	14.95	14.91	20.57	14.73	18.30	16.15	15.47	20.63	14.34	12.42	19.83	13.93	14.24	18.58	19.11	16.16	13.88	19.68	15.34	15.11
912	20.74	16.52	17.29	20.64	16.77	....	17.09	16.72	21.20	16.45	14.38	20.03	16.13	15.81	18.78	19.67	18.36	16.01	20.44	17.28	17.03
1,683	....	18.66	18.35	....	18.83	....	....	....	....	19.85	17.94	....	18.07	17.91	....	19.74	20.35	18.34	....	19.75	19.61

Table 2. Rate of Percentage Increase in Moisture Content for the Individual Blocks of Tamarack Heartwood When the Moisture Movement Was in the Different Structural Directions

Time, hours	Moisture gain in percentage of the oven-dry weight														
	Longitudinal					Radial					Tangential				
	Block No. 46	Block No. 47	Block No. 48	Block No. 49	Block No. 50	Block No. 61	Block No. 62	Block No. 63	Block No. 64	Block No. 65	Block No. 76	Block No. 77	Block No. 78	Block No. 79	Block No. 80
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1.25	1.28	1.21	1.36	1.18	0.49	0.36	0.48	0.48	0.30	0.36	0.49	0.30	0.30	0.49
10	3.09	2.97	3.00	3.07	3.10	...	...	...	...	...	...	...	...	...	...
23	4.99	4.95	4.95	4.88	4.79	1.66	1.58	1.52	1.63	1.56	1.52	1.65	1.50	1.46	1.71
46	7.66	7.57	7.55	7.61	7.49	...	...	...	...	...	...	...	...	...	...
71	9.74	9.83	9.79	9.54	9.57	3.81	3.60	3.52	3.38	3.42	3.52	3.42	3.54	3.29	3.73
119	12.47	12.52	12.73	12.55	12.33	5.47	5.18	6.28	5.01	5.04	5.04	5.14	4.99	4.81	5.20
166	14.49	14.38	14.57	14.65	14.41	...	...	...	...	...	...	...	...	...	...
287	17.76	17.30	17.57	17.38	17.34	10.32	10.43	10.12	9.18	9.42	9.41	9.30	9.38	9.14	9.36
671	19.71	19.84	19.93	19.36	19.65	15.72	15.43	15.70	14.74	15.12	15.18	14.98	14.84	14.92	15.61
912	20.66	20.33	20.62	20.22	20.38	17.51	17.56	17.33	16.91	17.10	17.12	16.94	16.77	16.93	17.38
1,683	....	....	....	....	....	19.35	19.57	20.06	19.81	19.98	19.37	19.76	19.11	20.10	19.71

Table 3. Comparative Rates of Percentage Increase in Moisture Content of Several Coniferous Woods When the Moisture Movement Was Confined to the Different Structural Directions

Kind of wood	Specific gravity*			Percentage moisture gain at half-saturation	Time to gain half-saturation moisture content		
	Longitudinal	Radial	Tangential		Longitudinal	Radial	Tangential
Balsam fir heartwood	.361	.414	.384	9.16	41	188	212
White spruce heartwood	.412	.424	.424	10.37	49	315	288
White spruce sapwood	.419	...	.485	10.32	53	...	312
Norway pine heartwood	.444	...	...	9.39	59	...	...
Norway pine sapwood	.491	.471	.443	10.00	62	319	308
Jack pine heartwood	.482	.503	.526	10.60	67	379	487
Black spruce heartwood	.518	.458	.533	9.87	68	273	370
Tamarack heartwood	.568	.582	.575	10.22	77	304	328

* Based on oven-dry volume.

The values used for comparative purposes were determined by reading, from the curves given in Figures 1, 2, and 3, the time necessary to gain half-saturation moisture content when the moisture movement was confined to the different structural directions. It was assumed that the blocks in which the moisture movement was confined to the radial and tangential directions would have the same half-saturation value as that attained by the blocks in which the movement was confined to the longitudinal direction. These values are given in Table 3.

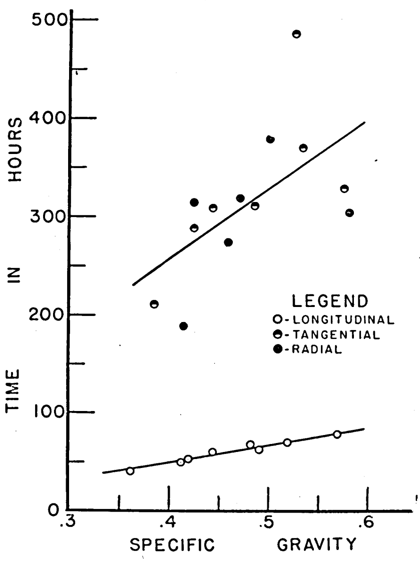

Fig. 4. Relation between the specific gravity of several coniferous woods and the time to half-saturation for moisture movement in the different structural directions

The data given in Table 3 and Figure 4 show that there is nearly a straight line relationship between specific gravity and the rate of percentage increase in moisture content in the longitudinal direction for the different kinds of coniferous woods having a range in specific gravity from about 0.35 to 0.55. The relationship between specific gravity and percentage increase in moisture content in the radial and tangential directions also can be represented by a straight line. These data, however, were not considered as significantly different and are represented by a single straight line. The variation of the data for the rate of increase in moisture content in the radial and tangential directions suggests that deviations characteristic for the different kinds of wood may exist. Further observations, based on samples from a number of different trees of each species, would be necessary in order to establish the significance of these deviations.

Both of the straight line curves in Figure 4 were fitted to the data by the method of least squares. Both curves show a negative time value at zero specific gravity. This suggests that these curves would not be straight lines throughout the entire range of specific gravity. If this is true, then the portion of the curve within the limits of the specific gravity of the coniferous woods approaches a straight line and has a slope of such magnitude that the curve would not pass through zero.

A consideration of the data given in Table 3 and Figure 4 shows that when the rates of moisture movement in the different structural directions of all the coniferous woods are compared, the rate of diffusion in the longitudinal direction is about five times the rate in the radial and tangential directions. These values agree well in order of magnitude with those reported by Stillwell (12) for oak and ash. They do not, however, agree with the results of Pidgeon and Maass (7) for white spruce, since their values showed that the rate of moisture movement in the longitudinal direction would be at least 20 times as rapid as the movement in the radial direction. As already pointed out, however, the work of Pidgeon and Maass, while called "diffusion," was done in the absence of air and involves the pressure movement of water vapor into the wood.

The same explanation can account for the lack of agreement between the results Pidgeon and Maass obtained for the relative rates of movement in heartwood and sapwood and the results given in Table 3 and Figure 4. These data show that there is no appreciable difference in the rates of moisture diffusion in the heartwood and sapwood of Norway pine and white spruce. The small differences in rates of percentage gain in moisture content which exist are those which could be predicted as the result of the differences in the specific gravity of the blocks which represented the heartwood and sapwood of the different kinds of wood.

It is of interest also to review the results given in Table 3 and Figure 4 in terms of the mechanism of moisture movement in wood. Water may move in wood below the fiber-saturation point in the following ways: (1) as vapor, the water vapor moving through the cell cavities and the intercellular openings; (2) as bound liquid, the water moving along the cell wall; and (3) as vapor and bound liquid, the water moving through the cell walls in the form of bound liquid and across the cell cavities in the form of vapor.

Based on the time to half-saturation, the rate of vapor movement through the cell cavities and intercellular openings in woods of different specific gravities would be influenced by three factors: (1) the average effective size of the openings through which diffusion may take place, (2) the number of openings through which diffusion may take place, and (3) the amount of water which must diffuse into wood to bring it to half-saturation. The amount of water necessary to bring the wood to half-saturation varies directly with the specific gravity of the wood. Consequently, the results given in Figure 4, particularly for movement in the longitudinal direction, are not greatly different from those which would be expected for vapor movement if the average effective size and number of intercellular openings did not vary appreciably for the heartwood and sapwood of the different kinds of wood. If there were no variation in the average size and number of the intercellular openings in the heartwood and sapwood of the different coniferous woods, the curves would be straight lines with a zero origin.

In studies of the rate of penetration of water into wood, Sutherland, Johnston, and Maass (13) found that the effectiveness of the openings in the sapwood of Norway pine and white spruce was more than 200 times that of the heartwood from the same tree. These results do not necessarily represent the effectiveness of the openings in relation to vapor movement, because the effectiveness as determined by the methods employed is a function of the fourth power of the radii of the average effective intercellular openings, while vapor diffusion would vary as the second power of the radii of the average effective intercellular openings. Nevertheless, these results show that there must be a decrease in either the number or size of the openings when the change from sapwood to heartwood takes place in these two woods. The effectiveness of the intercellular openings for vapor movement would vary directly with the change in number of openings and inversely as the second power of the radii of the average effective openings.

Stamm (9, 11) has obtained evidence which shows that the average effective size of the intercellular openings is not the same for sapwood and heartwood of different coniferous woods. For example, it was found (11) that the average effective capillary radius of the intercellular openings in slash pine sapwood was about 80 times larger than the average effective capillary radius of the intercellular openings in slash pine heartwood. Likewise, Stamm's results show that the average effective capillary radius of the intercellular openings in Douglas fir sapwood is about three times larger than the average effective capillary radius in Douglas fir heartwood. Stamm points out that the difference between the capillary dimensions of the heartwood and sapwood of

Douglas fir is much less than in slash pine. He attributes this difference to the presence of ring shakes in the heartwood of the Douglas fir, which would tend to increase the heartwood values. In confirmation of these results, it was found by a different method of measuring the size of the intercellular openings that the difference in maximum pore size for heartwood and sapwood of the same kinds of wood showed similar general relationships. Values for the average effective size of the openings in the sapwood of slash pine were found to be 80 to 150 times larger than the values for the average effective capillary openings in Alaska cedar, western red cedar, and Sitka spruce heartwood. While these were not the same woods for which the data are reported in Table 3 and Figure 4, there is no reason to believe that the variation in the average effective capillary radii of the heartwood and sapwood of the different kinds of wood included would not be of somewhat the same order of magnitude. The movement of vapor through openings which show these differences in size would be decidedly different, because, as already pointed out, the effectiveness of an opening from the standpoint of vapor movement would vary as the second power of the radii of the openings. In addition, it is unreasonable to expect that the change from sapwood to heartwood should be accompanied by a sufficient increase in the number of openings to compensate for the observed decrease in the average radii of the openings in the heartwood and thereby give a similar rate of diffusion of water vapor into the wood. In fact, the work of Griffin (2, 3) and Scarth (8) shows that the more probable thing to expect is a decrease in the number of openings in the change from sapwood to heartwood because of an increase in the number of aspirated pits.

The comparative rates of moisture movement in the different structural directions also suggest that moisture does not move in wood below the fiber-saturation point predominantly as vapor moving through the cell cavities and intercellular openings. Many more membranes are in series per unit thickness in the radial and tangential directions than in the longitudinal direction. Consequently, it seems reasonable to expect that the resistance to vapor movement would be increased more than is shown by the rate of moisture movement in the radial and tangential directions as compared with the longitudinal direction.

Additional evidence to show that moisture movement in wood is not predominantly in the form of vapor diffusion through the cell cavities and intercellular openings is found in the results of Johnston and Maass (5), Buckman, Schmitz, and Gortner (1), and Martley (6). Johnston and Maass have reported evidence which indicates that a decreased rate of flow of air through wood is obtained with increasing moisture content of the wood. Buckman, Schmitz, and Gortner found the maximum and average effective diameters of the intercellular opening decreased with increasing moisture content of the wood below the fiber-saturation point. It seems, therefore, that an increasing resistance to vapor movement would be obtained with increasing moisture content, yet Martley's results showed that more rapid rates of moisture movement were obtained at higher moisture contents.

The rates of moisture movement in wood as bound liquid when expressed on the basis of the time values necessary for half-saturation would be influenced by the following factors: (1) the amount of water which had to diffuse into the wood to bring it to half-saturation moisture content, and (2) the amount of cell wall substance along which liquid diffusion might take place. For bound liquid movement more water must diffuse into wood of a higher specific gravity to bring it to half-saturation, but there is also a proportionately greater amount of cell wall substance along which moisture movement can take place. Consequently, in order to explain the results given in Table 3 and Figure 4 in terms of bound liquid movement as the predominant mechanism, it would be necessary to assume that the added amount of wood substance per unit volume, which resulted in an increased specific gravity, was not effective for conducting water. In fact, it would be necessary to assume that the added amount of wood substance per unit volume not only was ineffective in conducting water as bound liquid but actually hindered the movement of water in all the structural directions. Because of this, the data given in Table 3 and Figure 4 can not be explained on the basis of moisture movement in wood entirely in the form of bound liquid.

For moisture movement in wood by diffusion through the cell wall as bound liquid followed by vapor diffusion across the cell cavities, the rate of movement when expressed in terms of the time to half-saturation would be governed by the following factors: (1) the amount of water which must move into wood to bring it to half-saturation; (2) the relative rates of moisture movement through the cell walls in the form of bound liquid and across the cell cavities in the form of vapor; (3) the relative distances which the moisture must travel in the form of vapor and in the form of bound liquid. If the rates of moisture movement through the cell wall as bound liquid and across the cell cavities in the form of vapor were not vastly different, the results given in Table 3 and Figure 4 are what would be expected on the basis of the amount of water which had to diffuse into the woods of different specific gravities to bring them to half-saturation moisture content. If there were no difference in the relative rates of moisture movement as bound liquid through the cell wall and as vapor across the cell cavities, the curves would be straight lines throughout the entire range of specific gravity and have a zero origin. However, as already stated, the fact that the curves do not pass through zero indicates that this relationship is not a straight line throughout the entire range of specific gravity.

On the basis of the results given in Figure 4, theoretical calculations can be made of the relative rates of moisture diffusion as bound liquid through the cell wall and as vapor across the cell cavities. The following values were used in the calculation: a cell wall thickness of 1.5×10^{-3} mm., a tracheid diameter of 3.5×10^{-2} mm., and a tracheid length of 3.5 mm. It should be noted that a value of about half the probable actual cell wall thickness was employed in the calculations. This value was used because it seems reasonable that a portion of the bound liquid diffusion will take place through the pit membranes; consequently the average length of the bound liquid diffusion path would be less than the thickness of the entire cell wall. The additional assumptions were made that the vapor diffused through half a tracheid length in passing from one cell to another in the longitudinal direction and diffused through a distance equal to the average diameter of the tracheid cavity in passing from one cell to another in the radial and tangential directions.

Applying the foregoing information to moisture movement through a distance of 35 mm. makes it possible to set up the following simultaneous equations: (1) for moisture movement in the longitudinal direction and (2) for moisture movement in the radial and tangential direction.

$$.0285x + 34.97y = 1 \qquad (1)$$
$$1.50x + 33.5y = 5 \qquad (2)$$

in which x is the relative rate of bound liquid diffusion through the cell wall; y is the relative rate of vapor diffusion across the cell cavity; 1 is the relative rate of diffusion in the longitudinal direction; and 5 is the relative rate of diffusion in the radial and the tangential directions.

Solving the equations gives values for x and y which are approximately in the ratio of 1 to 100. Because of a difference of this order of magnitude between the rates of diffusion in air as vapor and in cell wall substance as bound liquid, it is apparent that the relationship between specific gravity and rate of percentage increase in moisture content can not be a straight line throughout the entire range of specific gravity. With increasing specific gravity there will be a lengthening of the bound liquid diffusion path, a shortening of the vapor diffusion path and a decrease in the cross-sectional area through which vapor diffusion can take place, the relative decrease in cross-sectional area being greater for movement in the longitudinal direction than for movement in the radial or the tangential directions. Preliminary analysis of additional data collected for woods having a wider range of specific gravity supports the foregoing views and indicates that for movement in the longitudinal direction the relationship between specific gravity and rate of percentage increase in moisture content can be expressed by an equation of the following exponential type:

$$y = b + 10^{mx}$$

in which y is the time in hours, b is a constant, m is the slope, and x is the specific gravity.

SUMMARY

1. Blocks 2.5 by 2.5 by 5 cm. were cut to conform to the three structural directions of six different kinds of coniferous wood. In two of the woods, blocks were obtained from both the heartwood and sapwood. These blocks were dried in a uniform manner to a moisture content of approximately 5 per cent. After drying, they were coated with vulcanized rubber latex and shellac in such a manner as to confine the moisture movement to one structural direction of each wood. They were then transferred to a cabinet maintained at a relative humidity of 95 per cent and a temperature of 30° C., and observations were made of the increase in moisture content with time.

2. A relationship was found to exist between the rate of percentage increase in moisture content and the specific gravity of the wood.

3. For moisture movement in the longitudinal direction, the results show a straight line relationship between the rate of percentage increase in moisture content and specific gravity for both sapwood and heartwood of different kinds of coniferous wood having a range in specific gravity from about 0.35 to 0.55.

4. For moisture movement in the radial and tangential directions, the deviations from a straight line relationship with specific gravity are of sufficient magnitude to suggest that the rate of percentage increase in moisture content for movement in these structural directions may be somewhat characteristic of the different kinds of wood.

5. The rate of moisture diffusion in the longitudinal direction was about 5 times the rate in the radial and tangential directions.

6. The rates of moisture diffusion in heartwood and sapwood of Norway pine and white spruce are not significantly different.

7. The evidence presented shows that moisture moves in coniferous wood below the fiber-saturation point predominantly by bound liquid diffusion through the cell walls and vapor diffusion across the cell cavities. The results indicate that the rate of diffusion of vapor across the cell cavity was of the order of magnitude of 100 times the rate of diffusion through the cell wall.

LITERATURE CITED

1. Buckman, S. J., Schmitz, H., and Gortner, R. A. (1935) A study of certain factors influencing the movement of liquids in wood. Jour. Phys. Chem. **39**:103-120, illus.
2. Griffin, G. J. (1919) Bordered pits in Douglas fir: a study of the position of the torus in mountain and lowland specimens in relation to creosote penetration. Jour. Forestry **17**:813-822, illus.
3. ————. (1924) Further note on the position of the tori in bordered pits in relation to the penetration of preservatives. Jour. Forestry **22**(6) :82-83.
4. Hawley, L. F. (1931) Wood-liquid relations. U. S. Dept. Agr. Tech. Bull. 248, 34 pp., illus.
5. Johnston, H. W., and Maass, O. (1930) Penetration studies: the path of liquid penetration in jack pine. Can. Jour. Research **3**:140-173, illus.
6. Martley, J. F. (1926) Moisture movement through wood: the steady state. (Gt. Brit.) Dept. Sci. and Indus. Research, Tech. Paper No. 2, 22 pp., illus.
7. Pidgeon, L. M., and Maass, O. (1930) The penetration of water vapor into wood. Can. Jour. Research **2**:318-326.
8. Scarth, G. W. (1928) The structure of wood and its penetrability. Paper Trade Jour. **86**(17) :53-58, illus.
9. Stamm, A. J. (1927) The capillary structure of softwoods. Jour. Agr. Research **38**:23-67, illus.
10. ————. (1929) The fiber-saturation point of wood as obtained from electrical conductivity measurements. Indus. and Engin. Chem. Anal. Ed. **1**:94-97, illus.
11. ————. (1932) An electrical conductivity method for determining the effective capillary dimensions of wood. Jour. Phys. Chem. **36**:312-325, illus.
12. Stillwell, S. T. C. (1926) The movement of moisture with reference to timber seasoning. (Gt. Brit.) Dept. Sci. and Indus. Research, Tech. Paper No. 1, 29 pp., illus.
13. Sutherland, J. H., Johnston, H. W., and Maass, O. (1934) Further investigation of the penetration of liquids into wood. Can. Jour. Research **10**: 36-72, illus.